Hope for Oil Sands: Novel In-situ Recovery Methods

SPE Technical Luncheon, Horizontal Well and Heavy Oil Special Interest Group
19 April 2016
Tom Harding
We all know what the problems are for Oil Sands

- **Low Oil Prices** - Currently SAGD is mainly uneconomic
- **High Capital and Operating Costs** - contribute to the poor economics
- **Market Access limitations** – pipeline approval delays
- **Diluent costs are high** - for making bitumen transportable
- **Carbon Penalties Rising**
- **Environmental Issues** – carbon emissions and water use

We all see the consequences

- **Budget cuts** in producing companies
- **Project delays** and cancellations
- **Layoffs** of experienced staff
- **Lack of opportunity** for new graduates
- Companies entering receivership
- **Reduced revenue for governments**
- **Large budget deficits in Alberta**

Mayes, Edmonton Journal, 15 April 2016
Some recent headlines in Calgary Herald


“Alberta’s Rating Cut”, Darcy Henton, Calgary Herald, 16 April 2016

“Agency sees fall in global oil glut as supply outside OPEC declines”, Grant Smith, 15 April 2016

“Irving Oil studying expansion options from Energy East”, Rebecca Penty, 15 April 2016

“Still-mighty OPEC to talk output freeze – Oil price falls ahead of Qatar meeting where agreement seems unlikely”, Yadullah Hussain, 16 April 2016.

“Hope at Annual CAPP Forum – Oilpatch betting worst is over, eyes turnaround”, Deborah Yedlin, 16 April 2016.
What are the main uncertainties?

- Future supply and demand for oil
- Future oil prices - OPEC decisions
- Light heavy differentials
- Future carbon taxes
- Pipeline approvals
- Reservoir characterization
- Recovery technology for lower quality resources
What are the possible solutions?

- Cut costs
- Idle projects until oil prices recover
- Shut-in current production/mothball facilities
- Seek highest quality resources for development with current technology
- Modify existing operations to improve economics of current recovery method
- Develop lower cost, more sustainable recovery technology
Bitumen requires viscosity reduction in-situ

\[ \ln \mu = \sum_i x_i \ln \mu_i \]
SAGD Pros and Cons

• **Pros**
  – Heat delivery to formation
  – History of steam use
  – Water is cheap, abundant and exists in reservoirs
  – Many water treatment technologies exist
  – Water and steam have low viscosity

• **Cons**
  – Boiler inefficiency and heat losses during transport to reservoir
  – Significant energy removal from reservoir in form of hot produced water
  – High SOR requiring large steam plant, water treatment plant
  – Large carbon emissions due to fuel combustion on surface
  – Suppression of oil relative permeability
  – High capital and operating costs
  – Limited to highest quality resources
Water for Heat Transfer

- Water has advantages for delivering heat to formation
  - High combined specific (sensible) heat and latent heat of vaporization;
  - Total enthalpy nearly constant over a wide pressure range

Figure 1—Specific Heats and Heats of Vaporization of Some Elements and Compounds.

Figure 4—Enthalpy of Water (Sensible Heat), Latent Heat of Vaporization, and Enthalpy of Dry and Saturated Steam (Total Heat) at Different Pressures.

Source: Dr. S.M. Farouq Ali
Two-Phase Oil-Water Relative Permeability

- Flow rate of a fluid is directly proportional to its relative permeability.
- Relative permeability is in turn proportional to the saturation of the fluid in the pore space.
- When water is present in large amounts, oil flow relative permeability is suppressed and oil flow rate is reduced.
- In SAGD, water flows are 3 to 5 times higher than oil and water saturations are 3 to 5 times higher, suppressing the ability of oil to flow.

\[ q_l = \frac{k_l \cdot k \cdot A}{\mu_l} \cdot \frac{\Delta P}{L} \]
What Must New Recovery Methods Deliver?

• Compared to SAGD, improved in-situ recovery methods must have all of:
  – Lower capital and operating costs;
  – Similar or higher production and recovery
  – Greater energy efficiency
  – Lower environmental impact
    – Less water usage
    – Reduced carbon dioxide emissions

• Success will mean:
  – More attractive and robust economics; lower sensitivity of projects to commodity price, carbon taxes
  – Opportunity to develop poorer quality resources
  – Reserve additions
  – New business opportunities
  – Improved social license to operate

http://surmontenergy.com/operations/
Most Promising New Recovery Methods

- **Steam Additive Processes**
  - Steam/solvent co-injection – Long Lake field pilot in operation
  - Steam/NCG co-injection – Long Lake field pilot in operation
  - Steam/surfactant co-injection – preliminary assessment in progress

- **Hybrid Steam/In-situ Combustion Processes (e.g., SAGDOX)**
  - laboratory work nearing completion;
  - simulation capability under development

- **ESEIEH (RF heating with solvent injection)**
  - Field test in progress
  - Proprietary access through partnership

- **In-situ Reflux (resistive electrical heating with solvent injection)**
  - Proof of concept Physical model testing and initial simulation in progress
SAGDOX - Background


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% oxygen (v/v) in steam + O2 mix

<table>
<thead>
<tr>
<th>Test</th>
<th>Oxygen (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>14.9</td>
</tr>
<tr>
<td>17</td>
<td>6.6</td>
</tr>
<tr>
<td>21</td>
<td>6.5</td>
</tr>
<tr>
<td>22</td>
<td>2.3</td>
</tr>
</tbody>
</table>

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SPE 165509


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Stabilized ((CO2 + CO)/CO) Ratio vs. Oxygen Partial Pressure on a Wet Basis

Steam + Oxygen → tests 16 21 22

Other tests → air or air + water or oxygen + water

(Moore et al, 1994)

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Reacted Oxygen Requirements vs. Average Peak Temperature

(Moore et al, 1994)

Steam + Oxygen tests 16 17 21 22

(Other tests are air or air + water or oxygen + water)
SAGDOX Method

SAGDOX – Additional Features of the Process

• Ignition is assured in SAGDOX due to presence of steam temperatures
• High temperature combustion may be created and sustained at low O₂ concentrations
• Combustion temperatures are moderated by the presence of steam
• High reservoir temperatures may be achieved independent of pressure
• Partial upgrading of bitumen occurs in-situ
• Recovery process economics are improved: lower OPEX and CAPEX
• Producing gas/oil ratio is reduced by elimination of nitrogen
  – Improves relative permeability to oil
  – Eliminates erosion of downhole equipment due to high gas velocities
• Produced CO₂ useful in wind down of SAGD; Some CO₂ is sequestered
• GHG emissions and water usage may be reduced by up to 50 %
• May be applicable to high water saturation, shaley, thin reservoirs
SAGDOX – Challenges

• Simulation of the process is challenging: representative combustion reaction kinetics models; managing long run times; grid block averaging effects
• Ensuring complete combustion of oxygen in the reservoir – co-injection with steam helps
• Understanding the effects of the NCGs on the process
• Creating communication with vent gas wells and effective management of gas offtake
• Understanding the effect of high temperatures, while of a limited volume in the reservoir, on reservoir stresses
• Developing strategies to control location and movement of high temperature combustion to ensure integrity of downhole equipment
• Emulsions and corrosion; H₂S production
Physical Modeling
<table>
<thead>
<tr>
<th>Test Type</th>
<th>Location</th>
<th>Number</th>
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<tbody>
<tr>
<td>Bitumen Characterization</td>
<td>U of Calgary</td>
<td>1</td>
</tr>
<tr>
<td>Ramped Temperature Oxidation (RTO)</td>
<td>U of Calgary</td>
<td>8</td>
</tr>
<tr>
<td>Combustion Tube</td>
<td>U of Calgary</td>
<td>6</td>
</tr>
<tr>
<td>Conical Cell</td>
<td>U of Calgary</td>
<td>2</td>
</tr>
<tr>
<td>3D Physical Model</td>
<td>U of Calgary</td>
<td>4</td>
</tr>
<tr>
<td>3D Physical Model</td>
<td>AITF - Edmonton</td>
<td>3</td>
</tr>
</tbody>
</table>
Combustion Tube Temperatures in RTO Mode

Core CenterLine Temperature Profiles

U of C Test 421B, Nexen SAGDOX No. 5B, Long Lake No. 5B (Steam+Enriched Air)

- Start enriched Air injection and 0.75 h start temperature ramp at 40°C per hour to 450°C
- Stop enriched air injection and start helium flood; water injection continued

Temperature, °C

Run Time, h
## SAGDOX – Mathematical Modeling Program

<table>
<thead>
<tr>
<th>Activity</th>
<th>Specific Task</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction Kinetics Model Development</td>
<td>Matching of RTO and Combustion Tube Test Data</td>
<td>In progress – All 8 RTOs matched; One CT Test matched to date</td>
</tr>
<tr>
<td>Reaction Kinetics Model Development</td>
<td>Matching of 3D Physical Model Data</td>
<td>In Progress</td>
</tr>
<tr>
<td>Field-Scale Simulation</td>
<td>Sensitivity Study of Process Variables</td>
<td>In Progress, developing improved fluid characterization model</td>
</tr>
</tbody>
</table>
### Improved Reaction Scheme

\[ \text{Aromatics} + 0.26O_2 \rightarrow 0.1\text{OxidAro} + 0.85\text{Aromatics} \]  
\[ \text{Aromatics} + 0.10\text{OxidAro} + 12.159O_2 \rightarrow 0.30\text{Asphaltenes} + 4.018\text{CO}_2 + 4.911\text{H}_2\text{O} \]  
\[ \text{Resins} + 0.10\text{OxidAro} + 29.447O_2 \rightarrow 0.67\text{Asphaltenes} + 9.327\text{CO}_2 + 11.399\text{H}_2\text{O} \]  
\[ \text{Saturates} \rightarrow 3\text{LightOil} \]  
\[ \text{Asphaltenes} \rightarrow 0.78\text{Saturates} + 116.14\text{Coke} + 0.101\text{CO}_2 + 6.48\text{Gas} \]  
\[ \text{LightOil} + 12.91\text{Oxygen} \rightarrow 10\text{Water} + 6.75\text{CO}_2 + 2.25\text{CO} \]  
\[ \text{Gas} + 3.25\text{Oxygen} \rightarrow 3\text{Water} + 1.5\text{CO}_2 + 0.5\text{CO} \]  
\[ \text{Coke} + 1.125O_2 \rightarrow 0.75\text{CO}_2 + 0.25\text{CO} + 0.5\text{H}_2\text{O} \]

#### Table 5 Reaction kinetic parameters for improved model

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Pre-exponent factor A (day(^{-1}))</th>
<th>Activation Energy (E_a) (J/mol)</th>
<th>(\Delta H) (J/mol)</th>
<th>Oxygen Reaction order</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8</td>
<td>7.2×10(^4)</td>
<td>4.02×10(^5)</td>
<td>1.97×10(^4)</td>
<td>0.283</td>
</tr>
<tr>
<td>R9</td>
<td>1.44×10(^{11})</td>
<td>1.25×10(^5)</td>
<td>4.3×10(^6)</td>
<td>1.114</td>
</tr>
<tr>
<td>R10</td>
<td>1.44×10(^{11})</td>
<td>1.25×10(^5)</td>
<td>10.8×10(^6)</td>
<td>1.114</td>
</tr>
<tr>
<td>R11</td>
<td>1.44×10(^{12})</td>
<td>1.04×10(^5)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>R12</td>
<td>1.04×10(^{14})</td>
<td>1.34×10(^5)</td>
<td>0</td>
<td>0.732</td>
</tr>
<tr>
<td>R13</td>
<td>9.91×10(^{11})</td>
<td>7.76×10(^4)</td>
<td>4.83×10(^6)</td>
<td>1</td>
</tr>
<tr>
<td>R14</td>
<td>9.91×10(^{11})</td>
<td>5.76×10(^4)</td>
<td>2.43×10(^6)</td>
<td>1</td>
</tr>
<tr>
<td>R15</td>
<td>2.74×10(^{11})</td>
<td>1.38×10(^5)</td>
<td>1.5×10(^5)</td>
<td>1</td>
</tr>
</tbody>
</table>

From Yang et al (2016)
SAGDOX – Key Learnings

• High temperature combustion can be maintained at low oxygen concentration in the presence of steam
• Sufficient fuel for the combustion process is available in the form of residual oil in the steam-swept zone
• An improved reaction kinetics model for the steam/oxygen system has been generated from the laboratory data
Patents

- Nexen patent disclosures have been made on SAGDOX and variations on SAGDOX; one U.S. patent has been issued; 8 patents pending

Technical Publications


- Yang, M., Chen, Z., and Harding, T.G.: “An Improved Reaction Kinetics Model of In-situ Combustion for Pre-steamed Oil sands”, SPE-180728-MS to be presented at the SPE Canada Heavy Oil Technical Conference, Calgary, 7-9 June 2016.
In-situ Reflux

Figure 1. In-situ Reflux Process: End View Schematic Well Pair Case

- Reservoir Top
- Cold Bitumen Reservoir
- Steam Chamber
  - Bitumen & Steam condensate Drainage
  - Steam Reflux
- Main Heater/Injection Well
  - Water/Steam Interface
  - Bitumen/Water Interface
  - Water/Solvent Injection Line
  - Injection Well Heater
  - Production Well
- Production Well Heater (Optional)
- Reservoir Bottom
In-situ reflux side view of well pair
ISR Advantages over SAGD and Challenges

- Reduced CAPEX
  - Smaller central plant
    - Minimal water treatment equipment
    - No boilers
    - Reduced size of oil/water separation equipment
- Reduced OPEX
  - Lower energy requirement to re-vaporize saturated water
  - Minimal water treating chemicals required
- Improved Environmental Performance
  - Reduced water requirement
  - Lower treating requirements for produced water for reinjection
  - Lower CO₂ emissions
- Operational Improvements
  - Easy start-up/ re-start
  - Conformance control
  - Operational simplicity
- Other
  - Solvents or other fluids may replace water

Technical Challenges

- Heat transfer limitations
- Scale buildup around heater well
- Coke formation and fouling on heaters causing hot spots and plugging
- Asphaltene precipitation (re solvent injection)
- Single well operation feasibility
- Corrosion
- H₂S production
- Artificial lift of hot oil
- Heater failure
- Design and deployment of robust electrical heaters
- Power delivery and downhole temperature control
- Process operating variables
## ISR – Experimental Testing Program

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Location</th>
<th>Number</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen Coking/Aquathermolysis</td>
<td>SRC</td>
<td>1</td>
<td>In progress</td>
</tr>
<tr>
<td>Experimental Proof-of-Concept Testing – Phase 1</td>
<td>SRC</td>
<td>3</td>
<td>Complete</td>
</tr>
<tr>
<td>Experimental Proof-of-Concept Testing – Phase 2</td>
<td>SRC</td>
<td>3</td>
<td>In Progress (tests with water injection &amp; bitumen) 2 tests completed</td>
</tr>
<tr>
<td>Experimental Proof-of-Concept Testing – Phase 3</td>
<td>SRC</td>
<td>3</td>
<td>Planned (tests with solvent)</td>
</tr>
</tbody>
</table>
SRC Physical Model for ISR Testing

**Pressure Vessel**
- Length: 122 cm (48”)
- Diameter: 45.7 cm (18”)
- Pressure Range: up to 7,000 kPa
- Temperature Range: up to 250°C

**Data Acquisition System**
- Packed Core Cross Sectional View
- Multi-point Thermocouples in Uniform Grid Above Well (5-pt/TC)
- In Line Heater
- ISR Injection/Production Well
- Auxiliary Production Well

**Brine Pump**
- Make Up Brine Injection
- Thermocouples
- In Line Heater
- Insulated High Pressure Vessel with Strap Heaters (only 2 shown)

**ISR Well** (Injection/Production)
- Pressurized Liquid Production with Level Probe and Gas Head Space
- Gas Flow Meter
- Flow Control Valve or BPR
- TO H₂S scrubber and exhaust (not shown)

**Auxiliary Well** (Production)
<table>
<thead>
<tr>
<th>Activity</th>
<th>Specific Task</th>
<th>Group</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>History Matching</td>
<td>Experiment #4</td>
<td>SRC</td>
<td>Completed; used for planning and operation of Test #5</td>
</tr>
<tr>
<td>History Matching</td>
<td>Experiment #5</td>
<td>SRC</td>
<td>Planned for April</td>
</tr>
<tr>
<td>Fundamental mathematical modeling</td>
<td>Analysis of heat transfer in ISR</td>
<td>In-house</td>
<td>Complete</td>
</tr>
<tr>
<td>Coking and aquathermolysis</td>
<td>Develop reaction kinetics Model</td>
<td>In-house</td>
<td>Complete</td>
</tr>
<tr>
<td>Field-scale simulation</td>
<td>Conduct process sensitivity study; make production forecasts</td>
<td>In-house</td>
<td>In progress</td>
</tr>
</tbody>
</table>
ISR – Key Learnings

• The combined use of mathematical models and physical models allows acceleration of technology development
• 1 kW/m is the maximum practical limit for power delivery; limited by thermal conductivity of formation
• Higher heater power may be used if larger water injection rates are used
• A small amount of fluid injection (water) is necessary for the ISR process to work well; required to compensate for losses in thermal conductivity due to vaporization of connate water
• Solvent injection rates will be about 5 times those of water for equivalent convective heat transfer
• It is advantageous to have heaters in both injection and production wells in the two-well case
• Temperatures are high enough in ISR to cause pyrolysis of the bitumen and generation of H₂S
Patents


Technical publications


Themes and Messages

• SAGD has limitations both technical and economic and the future of in-situ oil sands development may rest on new recovery technologies – there are promising possibilities
• While at different stages of development, significant progress has been made in developing new methods
• The SAGDOX and ISR processes have been described along with the status of their development and their future potential for lowering costs and environmental impact of in-situ oil sands recovery
• Consideration is needed of potential impact on production operations and surface facilities of these recovery methods
• In future, Nexen desires to hold discussions with organizations having an interest in sharing costs of field testing of these new technologies
• There is hope for the oil sands industry that lower cost and more sustainable recovery technology can be developed to allow resources to be commercialized
• Support for R&D into new recovery technologies by industry and government is needed in order to ensure success
Thank you for your attention!

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